Review of Compressor Models and Performance Characterizing Variables

B. D. Rasmussen
Technical University of Denmark

A. Jakobsen
Technical University of Denmark

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B. D. RASMUSSEN
E-mail: bdr@et.dtu.dk

A. JAKOBSEN
E-mail: aj@et.dtu.dk

Department of Energy Engineering
Technical University of Denmark
Nils Koppels Allé, Building 402
DK-2800 Kgs. Lyngby, DENMARK

In this paper a method for categorization of compressor models is presented. The method is used in connection with a review of the compressor models presented in proceedings of the International Compressor Engineering Conferences at Purdue during the last 8 years. Trends in the development, purpose and use of compressor models are identified and discussed.

The traditional use of system-oriented variables like COP for describing the compressor performance has to some extent caused "confusion" when evaluating/comparing compressors. The different ways of describing the performance characteristics of a compressor is discussed and the general recommendations regarding the choice of performance characterizing variables is given.

NOMENCLATURE

Variable	Description	Unit	Variable	Description	Unit
$c_1..c_{10}$	Constants	[-]	**Greek**		
COP	Coefficient Of Performance	[-]	γ	Isentropic index	[-]
e	Specific exergy	[kJ/kg]	η_{CARNOT}	Carnot efficiency	[-]
f_Q	Heat loss factor	[%]	η_{CV}	Clearance volumetric eff.	[-]
h	Specific enthalpy	[kJ/kg]	η_E	Exergetic efficiency	[-]
$\dot{m}$	Mass flow	[kg/s]	η_{IS}	Isentropic efficiency	[-]
n	Polytropic exponent	[-]	η_{LEAK}	Leakage efficiency	[-]
p	Pressure	[kPa]	η_P	Polytropic efficiency	[-]
$\dot{Q}_E$	Refrigerating capacity	[kW]	η_T	Thermal efficiency	[-]
$\dot{Q}_{CP}$	Compressor heat loss	[kW]	η_{THERM}	Thermometric efficiency	[-]
T_C	Condensing temperature	[°C]	η_{VOL}	Volumetric efficiency	[-]
T_E	Evaporating temperature	[°C]	ρ	Density	[kg/m^3]
v	Specific volume	[m^3/kg]	**Index**		
V_{CV}	Clearance volume	[m^3]	1	Compressor inlet	
V_D	Displacement	[m^3]	2	Compressor outlet	
$\dot{V}$	Volume flow	[m^3/s]	CC	Compression chamber	
$\dot{V}_D$	Displacement rate	[m^3/s]	S	At constant entropy	
$\dot{W}$	Power consumption	[kW]	T	At constant temperature	

INTRODUCTION

In the open literature the term "compressor model" is used for describing many different types of models. When reviewing papers on this subject one may find the term used for models that describe only a part of a compressor like contact forces between moving parts, the acoustic properties of the compressor shell or the dynamic responses of the compressor suspension system. In this paper the term "compressor model" is used to describe mathematical models that focus on the thermodynamic processes from the suction stub to the discharge stub and how these processes control the flow of refrigerant. In other words models that calculate the performance of the compressor with respect to capacity and efficiency.

In the past 20 years a large number of compressor models have been presented in the open literature and at scientific conferences. An important source of papers on compressor models is the proceedings of the International Compressor Engineering Conferences (ICEC) at Purdue [1]. It is argued that the models found in the ICEC-proceedings are representative of the general development within this area of research.

A review of the ICEC-proceedings of the last 10 years shows that more than 100 papers involving compressor models (as defined above) have been presented. These models cover many different types of compressors, models, and modeling purposes. In order to identify trends in the development and use of compressor models, the ICEC-proceedings from 1992, 1994, 1996, and 1998 were reviewed and an attempt was made to categorize the models.

METHOD OF CATEGORIZATION

The method chosen for categorization is based on the detail level of knowledge needed to develop the model. Figure 1 shows the six main categories of compressor models organized on a scale of the knowledge needed for developing the model. Models that require the lowest level of knowledge are called "Black-box" models and models that require the highest level of knowledge are called "White-box" models. On this scale, all models falling between these limits are called "Gray-box" models.

BLACK-BOX

- Statistical correlations based on system performance variables

$$\dot{Q}_E, COP, \eta_{CARNOT} = f\left(T_E, T_C\right) = c_1 - c_2T_E - c_3T_C - c_4T_E^2 - c_5T_ET_C - c_6T_C^2 - c_7T_E^3 - c_8T_CT_E^2 - c_9T_ET_C^2 - c_{10}T_C^3$$

- Statistical correlations based on compressor performance variables

$$\eta_{IS}, \eta_{VOL} = f(T_E, T_C) = c_1T_E + c_2T_C + c_3T_ET_C + c_4T_E^2 + c_5T_C^2$$

- Process-oriented models

$$\eta_{IS}, \eta_{VOL} = f\left(p_2/p_1, \dot{V}_1, T_E, V_{CV}/V_D\right)$$

- Phenomena-oriented models (one or more control volumes)
- Construction-oriented models (many control volumes, dynamic models)
- Distributed models (partial differential equations...)

WHITE-BOX

Figure 1: Categorization of compressor models

The equations in "Black-box" models represent only numerical relations between inputs and outputs, and do not directly describe any physical phenomena. The equations in "Gray-box" models may also contain numerical relations based on statistics but will further contain equations describing physical phenomena from fundamental equations. In a "White-box" model all processes are described using fundamental equations only (conservation of mass, energy and momentum, generation of entropy, Navier-Stokes equations, etc.). A true "White-box" model of a compressor may probably never be developed – the knowledge needed for developing such a model being too extensive to gather and organize.

The first two categories contain compressor models that use correlations based on statistical data. In the first category the model outputs are system performance characterizing variables like refrigerating capacity, COP and Carnot efficiency. These are often valid only for testing conditions specified by ISO, CECOMAF, ASHRAE, ARI, etc. In the second category compressor performance characterizing variables like isentropic and volumetric efficiencies are selected as model outputs. Polynomial equations are often recommended for models of these categories where all polynomial coefficients are determined from experimental data (compressor map) [2].

These two categories of models are the ones that compressor manufacturers often supply with their products or use for their computer aided product selection programs (CAPS). They do not contain any explicit knowledge about the internal processes and their interactions, and they are consequently rarely found in the ICEC-proceedings.

The third category also contains models based on statistical data but these models does to some extent describe the compressor performance using geometric variables like compressor displacement and clearance volume ratio. As for the second category, compressor performance characterizing variables like isentropic and volumetric efficiencies are often chosen as outputs.

For the next three model categories the compressor is divided into individual parts (control volumes) that are coupled together in terms of flows of mass and energy (and entropy/exergy). The first of these categories contain the phenomena-oriented models where the division of the compressor into control volumes is based on general phenomena and not necessarily on the individual components of the compressor. Typically, these models are "centered" around the model for the processes in the compression chamber. Figure 2 shows an example of this type of model. Here the compressor is divided into three control volumes (pre-compression, compression, and post-compression). Phenomena-oriented models can be steady state models or dynamic models. In the steady state models the compression process is discretized (separated) into part processes such as suction, compression, discharge and expansion. In the dynamic models the changes in compression chamber volume and the changes in refrigerant properties are described as continuous functions of time.

As the number of control volumes is increased the models become construction-oriented in the way that the control volumes each represent a specific component of the compressor. In each of the control volumes the processes are described using differential algebraic equations (DAE's). Figures 3 and 4 show two examples of construction-oriented models.

The category closest to the "White-box" end of the scale contain models that are based on a construction-oriented model but contain one or more distributed sub-models for describing some of the processes in the control volumes. The distributed sub-models use partial differential equations (PDE's) often solved with finite element or finite difference methods.

As mentioned before, a "true white-box" model using only PDE's for describing the processes in the control volumes may probably never be developed.

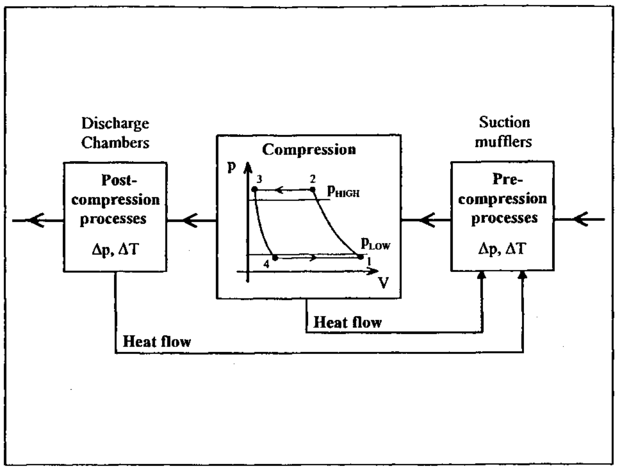

Figure 2: Phenomena-oriented model (example)

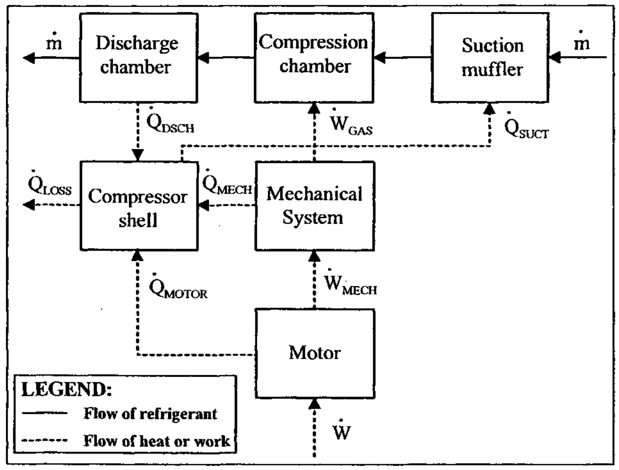

Figure 3: Construction-oriented model (example)

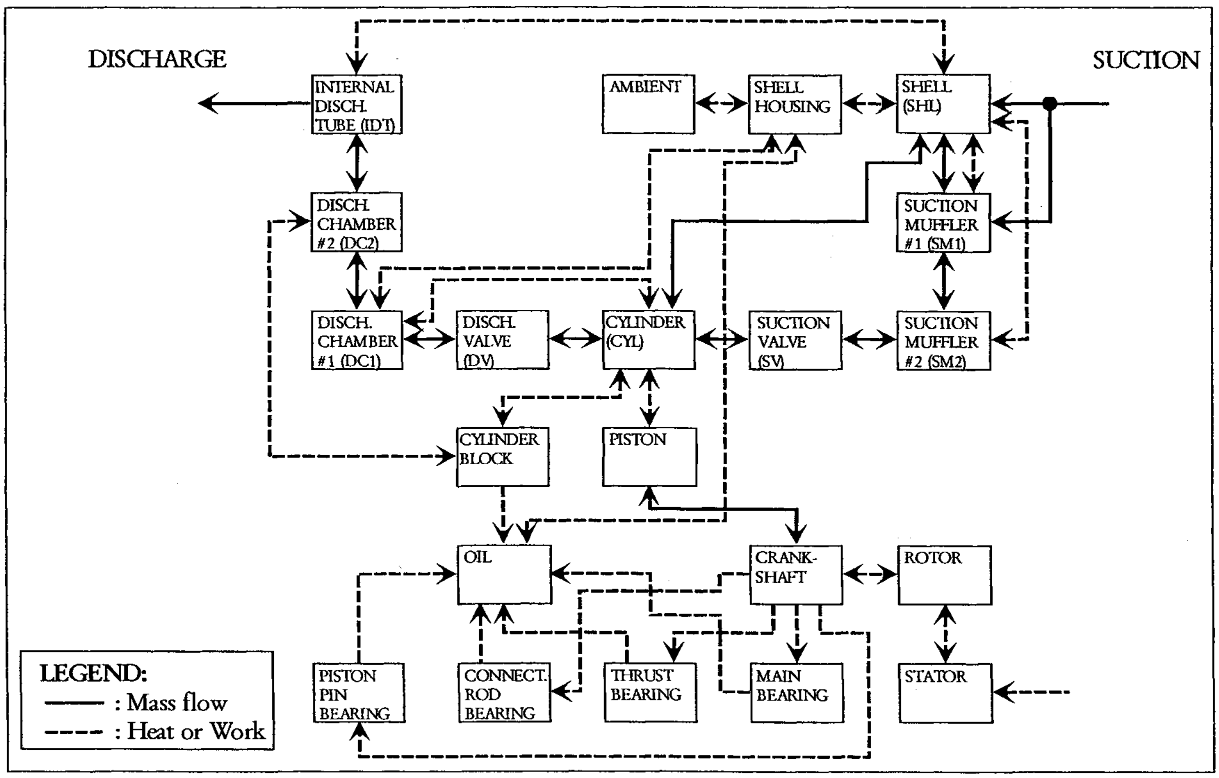

Figure 4: Construction-oriented model (example) [3]

IDENTIFICATION OF TRENDS

When applying the method of categorization to the models presented in the ICEC-proceedings it is found that often the models are not described sufficiently detailed for a precise categorization. Often more information than presented in the paper is needed to determine whether the model is phenomena-oriented or construction-oriented.

Most of the compressor models found in the ICEC-proceedings fall into the categories phenomena-oriented, construction-oriented while only a few come close to be categorized as distributed models. This is also natural as most of the purposes of these models are to assist in energy optimization of the compressor and in gaining knowledge about the internal processes and their interactions.

When reviewing the paper presented during the last four conferences (1998, 1996, 1994, and 1992) it can be observed that the number of construction-oriented models is increasing and the number of phenomena-oriented models is decreasing. In other words, the construction-oriented models make up a larger part of the models presented. Only in the recent proceedings are models presented that almost qualify as distributed models.

Using the method of categorization, trends have been identified in the following areas:

Model Complexity: A general trend in the models presented in this period is the increasing numerical complexity of the models. This trend is not only a result of the opportunities gained by the increase in computing power of PC's and workstations, but it is also a result of an increasing need for more detailed knowledge about the processes inside compressors.

Model Purpose: The review of models have showed that the purpose of the models have changed during the years. Previously compressor models were developed for very specific investigation purposes, and this meant that not all parts of the compressor had to included in the model. Now the models seem to be more general comprising more and more components allowing the model to be used for different types of investigations.

The following list shows the most often found purposes for developing the models presented:

- Impact of refrigerant properties on compressor performance: The phase-out of CFC and HCFC refrigerants has made it necessary to optimize existing components for other refrigerants than they were designed for. The use of compressor models to optimize suction mufflers, valves, and discharge chambers for alternative refrigerants has become one of the major modeling purposes.
- Variable speed capacity control: The international requirements for increases in energy efficiency of domestic refrigerators and freezers have made it feasible to use variable speed as a method for capacity control. Models have been used to evaluate the influence of speed on performance and to investigate how components can be optimized for variable speed.
- Cylinder heat transfer: This area of research has been represented in almost all ICEC-proceedings since the first conference in 1972, but recently general construction oriented compressor models have been used for comparative studies of the many different sub-models for the cylinder heat transfer coefficient.
- Pressure controlled valves: The investigation of the dynamic behavior of pressure controlled valves (e.g. Reed valves) requires that the model includes the other dynamic processes with the same time scales. Valve modeling has therefore become closely connected to compressor modeling and the few models that almost qualify as distributed models have valve investigation as purpose.

Model structure: Traditionally, the program code in compressor models have been structured for simulation of either a specific compressor or a specific compressor series. The programming method used is often described as "functional"-programming. In the resent ICEC-proceedings object-oriented modeling methods have been presented. These methods divide the compressor into parts (modules) that can be described generally (like cylinder, mufflers, compression mechanisms, motors, etc.). The advantage of this method is that a simulation model of almost any type of compressor can be constructed by combining general component models from standard libraries. The object-oriented method itself is not new, but its application to compressor modeling is.

With the many different investigation purposes it is not always obvious which variables to choose for describing the performance of a compressor. Traditionally, some confusion about the nature of compressor performance variables has existed and this has among other thing lead to COP being used as a measure for compressor energy efficiency only. The next sections of this paper will discuss the choice of performance characterizing variables for compressors.

PERFORMANCE CHARACTERIZING VARIABLES

If the compressor is seen as single control volume, a complete description of its performance requires that the following characteristics must described:

- Capacitive performance
- Energetic performance
- Thermal performance

Each of these three performance characteristics can be described using variables that are either system oriented or compressor oriented.

The system oriented variables express the capacitive performance of the compressor in terms of refrigerating capacity $\dot{Q}_E$, the energetic performance in terms of *COP/EER* and/or η_{CARNOT}, and the thermal performance in terms of heat loss $\dot{Q}_{CP}$ or discharge gas temperature T_D.

The refrigerating capacity depends on the enthalpies of the refrigerant entering and leaving the evaporator and these are normally expressed indirectly using the parameters subcooling of the liquid and the ratio between useful and unuseful superheat. These parameters are determined by factors that are not influenced by the compressor, and this complicates the evaluation of the compressor performance from system-oriented variables only.

In the resent years different electronic systems calculating the COP from measured pressures, temperatures, flows, and power consumption has been marketed as compressor surveillance and maintenance system. These systems have in many cases lead to a misuse of COP as a measure for compressor performance. Any changes observed in COP have been ascribed to changes in compressor efficiency neglecting the influence on COP of other, and not at all compressor-related, parameters. The use of system oriented variables only to characterize the compressor performance is therefore not precise.

A much higher precision in characterizing the performance of a compressor can be obtained by using so called compressor-oriented variables. These can be divided into groups according to the phenomena they describe. The following list of compressor performance characterizing variables is not complete, but the variables selected represent the most often used:

Capacitive performance

The capacitive performance of a compressor relates the actual flow of refrigerant to an ideal flow assuming no losses. Most often the capacitive performance is described by the volumetric efficiency relating the volume flow of refrigerant in the compressor suction stub to the displacement rate of the compressor. For dynamic compressors such as turbo compressors, a displacement rate cannot be defined and consequently a volumetric efficiency can not be used for these compressors.

The mathematical definition of the volumetric efficiency is given in Table 1. The volumetric efficiency accounts for many different phenomena (clearance volume re-expansion, pressure drops in valves, internal heating of suction gas, etc.). It is therefore relevant to see it as the product of the following individual efficiencies:

Volumetric	Thermometric	Clearance volumetric	Leakage
$\eta_{VOL} \equiv \frac{\dot{V}_1}{\dot{V}_D}$ $\eta_{VOL} = \eta_{THERM} \cdot \eta_{CV} \cdot \eta_{LEAK}$	$\eta_{THERM} \equiv \frac{\rho_{CC}}{\rho_1}$	$\eta_{CV} \equiv \frac{V_D - V_{CV}\left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}}}{V_D - V_{CV}}$	$\eta_{LEAK} = \frac{\eta_{VOL}}{\eta_{THERM} \cdot \eta_{CV}}$

Table 1: Definitions of volumetric efficiencies

The thermometric efficiency includes losses in capacity caused by internal heating of suction gas and pressure drop between suction stub and compression chamber during the suction process. The clearance volumetric efficiency accounts for the re-expansion of the gas caught in the clearance volume. The definition presented assumes that the refrigerant is an ideal gas, the expansion is reversible and adiabatic starting at a pressure equal to the discharge pressure and ending when the pressure in the compression chamber becomes equal to the pressure in the suction stub. Other definitions exist that use different processes, pressures and/or real gas properties. The leakage efficiency is not well defined except for the fact that it can be calculated from the volumetric efficiency, the thermometric efficiency, and the clearance volumetric efficiency. It holds information about a range of capacitive losses caused by leakage from the compression chamber to the suction side, from back-flow through valves, etc.

Energetic performance

The energetic performance of a compressor can be described by several different efficiencies comparing the actual power consumption to the power consumption of a reference process. The difference between these efficiencies lies in the choice of reference process. Most often a reversible adiabatic compression process is used for expressing the energy efficiency (isentropic efficiency) of a compressor. Other reference processes can be used like polytropic or isothermal process. The isothermal process is used for compressors with low operating frequencies, where it is more relevant to compare the actual compression process with an isothermal process.

Isentropic	Polytropic	Exergetic	Thermal
$\eta_{IS} \equiv \frac{\dot{m}\left(h_{2,S}-h_1\right)}{\dot{W}}$	$\eta_P = \frac{\dot{m}\frac{n}{n-1}p_1 v_1\left(\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}-1\right)}{\dot{W}}$	$\eta_E \equiv \frac{\dot{m}\left(e_2-e_1\right)}{\dot{W}}$	$\eta_T \equiv \frac{\dot{m}\left(h_{2,T}-h_1\right)}{\dot{W}}$

Table 2: Definitions of energetic efficiencies

A polytropic process can also be used as reference process but will require the specification of a polytropic exponent. In a compressor heat transfer to an from the refrigerant plays an important role, and many arguments for using a polytropic efficiency is based on the polytropic process being able to take heat transfer into account. However, the heat transfer processes in a compressor comprise both heat transfer to and from the refrigerant. A polytropic process with fixed exponent can describe the net effect of the heat transfer on the process endpoint but it is not able to describe the course of the process itself.

The exergetic efficiency compares the change of specific exergy to the power consumption. The value for the specific exergy of the refrigerant depends on the temperature of the compressor surroundings.

Compared to an isentropic efficiency the use of a polytropic efficiency with a fixed exponent gives no more information about the energetic performance of the compressor. Since the polytropic exponent is highly refrigerant dependant, a fair evaluation of the efficiency of the same compressor with different refrigerants is not possible.

For a compressor with a given power consumption and mass flow a decrease in heat loss from the compressor, and consequently an increase in discharge gas temperature, would result in an increase in exergetic efficiency, but the isentropic efficiency would remain the same. This increase in exergetic efficiency may be a disadvantage to the refrigeration system because it might lead to a higher condensing temperature or give rise to problems with oil temperature. On the other hand it may be an advantage for systems using the discharge gas in a heat recovery system.

This simple problem shows that the exergetic efficiency holds information that the isentropic efficiency doesn't. The use of the exergetic efficiency for evaluating the energetic performance of a compressor is therefore recommended as an addition to using an isentropic efficiency.

Thermal performance

The thermal performance of a compressor is usually not very well described in compressor models if described at all. At steady state conditions, the heat loss from a small hermetic compressor may be up to 70 % of its power consumption. For larger compressors with active cooling (air, water, oil, refrigerant) the heat loss is less important but may still account for 10 – 20 % of the power consumption.

There is no generally accepted method for describing the thermal performance of a compressor. One method is to use the heat loss factor f_Q comparing the actual heat loss to the power consumption. It is defined as shown in Table 3.

Heat loss factor
$f_Q \equiv \frac{\dot{Q}_{CP}}{\dot{W}}$

Table 3: Definitions of thermal performance variables

CONCLUSIONS

Depending on the purpose of a compressor model, the performance characterizing variables should be selected so that they support the purpose of the model by reflecting any the consequences of changes in the phenomena of interest. The selection of variables for a compressor model is not always evident and situations may occur where the variables selected do not support the purpose of the model.

Evaluating the performance of a compressor from system-oriented variables is a less precise and much more complex procedure compared to evaluating the performance from compressor oriented variables.

It is generally recommended to use the isentropic efficiency and the exergetic efficiency for evaluating the energetic performance – for compressors with very low operating frequencies the isothermal efficiency may be used instead of the isentropic efficiency or even better in addition to it.

The use of a polytropic efficiency for evaluating the energetic performance is not generally recommended. It holds no more info than the isentropic efficiency, it is more complex to use and it is difficult to use for comparisons of different refrigerants.

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